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# Radiation Damage and Waste Management Options for the SOMBRERO Final Focus System and Neutron Dumps

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**Abstract**

Previous studies of the safety and environmental aspects of the SOMBRERO inertial fusion energy (IFE) power plant design did not completely address the issues associated with the final focus system. While past work calculated neutron fluences for a grazing incidence metal mirror (GIMM) and a final focus mirror, scattering off of the final optical component was not included, and thus, fluences in the final focus mirror were significantly understimated. In addition, past work did not consider neutron-induced gamma-rays. Finally, power plant lifetime waste volumes may have been underestimated as neutron activation of the neutron dumps and building structure were not addressed. In the present work, a modified version of the SOMBRERO target building is presented where a significantly larger open solid-angle fraction (5%) is used to enhance beam smoothing of a diode-pumped solid-state laser (DPSSL). The GIMMs are replaced with transmissive fused silica wedges and have been included in three-dimensional neutron and photon transport calculations. This work shows that a power plant with a large open solid-angle fraction, needed for beam smoothing with a DPSSL, is acceptable from tritium breeding, and neutron activation points-of-view.

## 1. Introduction

The SOMBRERO conceptual design, which originally used a KrF laser driver, has been modified for a DPSSL driver.[1] The open solid-angle fraction has been increased from 0.25% to 5%, while the number of beams (60) has been kept constant. A smaller open solid-angle fraction may be acceptable, but this work assumes a conservative design. Instead of using GIMMs, the modified design uses transmissive wedges for the final optical component. The rest of the reactor geometry has been kept the same as presented in the SOMBRERO report, except the size of the optics and the neutron dumps has been increased to accommodate the larger open solid-angle fraction. Neutron dumps partially shield the final focusing mirrors from neutrons that could scatter off of the back wall. Since the neutron dumps are larger in the new design, the final focusing mirrors must be moved farther from the beam axis and the bending angle at the wedge must be increased as well. This requires an increase in the wedge thickness. To avoid unreasonably thick wedges one possible solution consists of splitting each beam in two and using two focusing mirrors standing on either side of the neutron dump. The two final focusing mirror arrays send their respective beams to a single array of wedges. Alternatively, one could use a rectangular or elongated configuration for the beams, as opposed to a square configuration. This would require rectangular penetrations in the chamber and rectangular neutron dumps and result in a considerable reduction of the bending angle.

## 2. Overview of SOMBRERO

In order to validate our methodology we have reviewed the previous work that was completed for the KrF-driven SOMBRERO IFE power plant design.

It has been found that neutron-induced gamma-ray doses in the final optical or focusing components were not considered. Recent work in support of the National Ignition Facility indicates that gamma-ray doses can be of great importance when estimating the lifetime of optical components.[2] It has also been found that the GIMM was not modeled in order to consider the neutron scattering in that element, and only 1-D scaling was performed in order to achieve the fast neutron flux at the position of the final focusing mirror. The present work shows this flux was then underestimated and that it is essential to perform 3-D calculations that consider the secondary neutrons scattered by the GIMM. Another problem found when trying to predict the expected lifetime for the optics is the fact that a clear fast neutron fluence limit has yet to be determined. The SOMBRERO study estimated the optics lifetime assuming a range of fluence limits. A complete analysis would require more material data about the fast neutron and gamma-ray fluence limits.

## 3. Computational methods

3-D neutronics calculations have been performed using the TART98 Monte Carlo neutron and photon transport code.[3] The present work utilized the ENDL neutron transport and the EPDL photon transport cross section libraries.[4-5] A point neutron source was used at the origin emitting neutrons isotropically with the SOMBRERO target energy spectrum. The model includes the detailed radial build of the SOMBRERO design at the midplane for the blanket/reflector, which has an overall thickness of 1 m with an inner radius of 6.5 m. The 1.5-m-thick inner shield and the cylindrical reactor containment building are included. The neutron dumps have been modeled using an aspect ratio (depth divided by diameter) of unity. The wedges are located 30 m from the target and are made of pure fused silica operated at high temperature (around 400 °C) to promote self-annealing. A baseline wedge thickness of 3 cm was used. All the free space inside the reactor building is filled with xenon gas at 0.5 torr in order to protect the first wall from target x-rays and debris. Dose rates and fluxes from gamma-rays and fast neutrons have been obtained at the optical elements. The results for the final focusing mirrors are reported in cylindrical zones around the neutron dumps in order to approximate their location. Only neutrons with energies > 100 keV are counted in the fast flux.

The ACAB activation code has been used with the FENDL/A-2.0 activation cross section library for subsequent activation calculations.[6-7] Calculations have been completed assuming 30 full-power-years (FPY) of irradiation, using a fusion power of 2677 MW. Results have been obtained for cooling times of up to 100 years. We have reported the results of waste disposal rating (WDR) and contact dose rates for the optical elements and for the neutron dumps and building shell. For the activation calculations typical impurities have been included in the $SiO_2$ used for the wedges and the final focusing mirror substrate (typical impurities have been considered[8]). For the dielectric coating of the mirrors, calculations have been performed for two different materials: $MgF_2$ and ZnS.

## 4. Results

The neutronics calculations show that adequate tritium breeding is possible with 5% open solid angle fraction (TBR = 1.16).

The fast neutron and gamma fluxes at the wedges are $9.54 \times 10^{12}$ n/cm$^2$s and $4.55 \times 10^{12}$ g/cm$^2$s, and the dose rates are 109 Gy/s and 36 Gy/s for fast neutrons and gamma-rays, respectively. *Figure 1* shows the same parameters for the final focus mirror. Particles that scatter off of the wedges dominate these fluxes, so these results scale with the open solid-angle fraction and the wedge thickness.

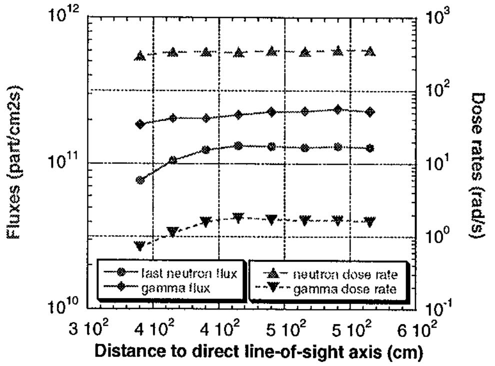


**Fig. 1.** Fast neutron and gamma fluxes and dose rates at the final focus mirror position.

For a range of fluence limits from $10^{20}$ to $10^{22}$ n/cm$^2$ for the wedges (limits that were used in SOMBRERO report to study the lifetime of the GIMMs), the lifetime of the wedges would be 0.33 to 33 FPY. For this range of lifetimes, the WDR would range from $7.5 \times 10^{-5}$ to $1.2 \times 10^{-2}$, and the volume of the waste from these components after 30 years operation would be between 17 and 1600 m$^3$. This result is conservative given that it is expected that the wedges would be self-annealing so that they would be more survivable.[9] To estimate the lifetime of the final focus mirrors we have used the range of fluence limits for dielectric coated mirrors that appear in the SOMBRERO report. The lower end of this range, $10^{17}$ n/cm$^2$, would result in a lifetime too short to be practical. For a range of $10^{18}$ to $10^{19}$ n/cm$^2$ the lifetime of the mirrors would be 0.25 to 2.5 FPY. The estimated waste volume is 270-2700 m$^3$ after 30 years operation assuming that each time the dielectric coating has to be replaced, it is removed together with the fused silica substrate. The volume of waste could be greatly reduced, as it may be possible to reuse the substrates. The WDRs are shown in *Table I*, for the substrate and for two different dielectric coatings.

Table I. WDR for the final focusing mirror.

| Mirror components | Fluence limit $= 10^{18}$ n/cm$^2$ | Fluence limit $= 10^{19}$ n/cm$^2$ |
|---|---|---|
| Substrate | 6.6E-7 | 6.3E-6 |
| ZnS coating | 9.8E-7 | 9.7E-6 |
| $MgF_2$ coating | 6.6E-12 | 6.6E-10 |

*Figure 2* shows the contact dose rates for the wedge and the final focus mirrors as a function of cooling time. For each of the optical elements we have considered the longer lifetime, in order to be conservative.

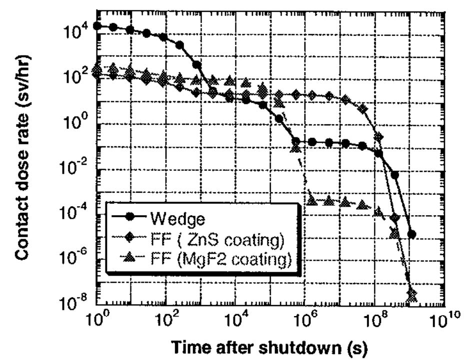


**Fig. 2.** Contact dose rates for the wedge and final focus mirror.

Even though both the wedges and the final focusing mirrors would require remote recycling, $MgF_2$ is recommended as dielectric coating material as it gives lower values of WDR and contact dose rate.

As the first wall and blanket easily meet waste disposal rating criterion for shallow land burial (WDR < 1) only the results for the concrete of the building and the neutron dumps are shown in *Table II.* As would be expected due to their exposure to line-of-sight neutrons, the neutron dumps have a much higher WDR value than the building and it increases slowly with the open solid-angle fraction. This makes the waste management for the concrete rather insensitive to the open solid-angle fraction. It should be noted that the neutron dumps are unimportant from the waste volume perspective (they are ~ 0.1% of the building shell volume in the largest case), and thus, the total waste volume does not change as the open solid-angle fraction is increased.

Table II. WDR for the concrete.

| Open solid angle | Neutron dumps | Building |
|---|---|---|
| 0.25% | 4.39E-1 | 4.86E-4 |
| 5% | 4.72E-1 | 1.20E-2 |

The contact dose rates for the building and a single neutron dump are shown in *figure 3* as a function of the cooling time after shutdown. The neutron dumps produce a significantly higher contact dose rate than the building shell. The contact dose rate of the building shell is independent of the solid-angle fraction.

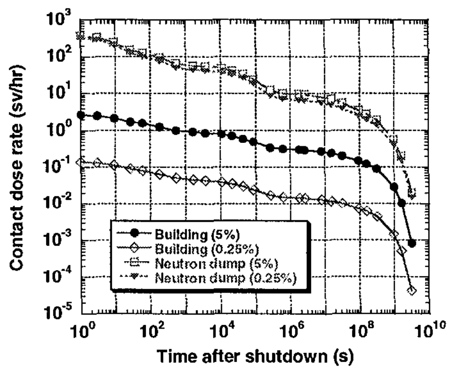


**Fig. 3.** Contact dose rate for the building shell and neutron dump after shutdown.

## 5. Conclusions

Adaptation of the SOMBRERO power plant design for use with a DPSSL driver probably requires an increase in the open solid-angle fraction. The fast neutron flux at the final focusing mirror is dominated by neutrons scattered off of the wedges and so it is proportional to the open solid-angle fraction, as well as the thickness of the wedges. As a result, a smaller value of the open solid-angle fraction will translate directly into a longer lifetime of the final focus mirrors. Thus, increases in the laser bandwidth, which will allow a decrease in the open solid-angle fraction, have a large benefit. It is recommended that wedges be as thin as practical as this will also reduce the scattered radiation. Contact dose rates and waste management are rather insensitive to the open solid-angle fraction. Experimental data on radiation damage, survivability, annealing, and recycling of optical components are needed. Such data must include not only neutrons but gamma-rays as well.

## Acknowledgments

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